

MICROWAVE STIFFENING SYSTEM FOR CERAMIC EXTRUDATES

Background Of The Invention

[0001] The present invention relates to a processing system and method for stiffening an extruded body using microwave energy to provide improved handling and to reduce handling-related deformation defects prior to drying and firing operations. More particularly the invention facilitates continuous microwave heating of a wet ceramic extrudate as it is formed into a honeycomb type article.

[0002] The extrusion of plasticized material mixtures into multicellular (i.e., honeycomb) bodies involves a delicate balance of softness/deformability (for shape molding) and structural integrity (for shape retention). Such mixtures include inorganic ceramic powders, a binder system and a liquid component, the amounts of which are tightly controlled to maintain low pressure/torque/temperature during the extrusion process while creating a self-supporting body which is able to be handled upon formation.

[0003] Generally as the viscosity of the plastically deformable material is lowered, the wet, formed structure or article tends to collapse due to insufficient self-support. Conversely, as the viscosity of the plastically deformable material is increased to create self-support, forming of the material tends to require significantly higher forming pressure which in turn means that it becomes necessary to use heavier equipment, more substantial forming members and abrasion resistant parts.

[0004] Plastically deformable materials of the type described also typically include an organic binder component having a thermal gel point. As the temperature is increased toward the gel point, the viscosity of such materials decreases but when the gel point is reached there is a very rapid increase in the viscosity with increasing temperature. Therefore, plastically deformable materials of this kind tend to be worked and formed at temperatures just below the gel point of the organic binder.

[0005] Taking advantage of this gelling reaction, it has been proposed in U.S. Pat. No. 5,223,188 to use RF or radio frequency energy to heat a structure formed from a plasticized material to provide improved wet strength for better handling and processing capabilities. However, challenges exist in applying RF energy uniformly

to the extruded structure, preventing the formation of extrudate skin defects, and controlling radiation leakage. Therefore, there exists the need for an improved system and method for uniformly heating a continuously moving, wet ceramic extrudate to provide improved handling before drying and firing.

Summary Of The Invention

[0006] There is provided an apparatus and process for applying microwaves to stiffen a newly formed ceramic extruded structure for providing substantially improved wet strength and handling prior to drying and firing. The apparatus includes a microwave source for producing energy in the frequency range of 100 MHz to 30 GHz; a microwave applicator comprising a chamber having a flow axis, an inlet, an outlet, and a support for transporting the extruded ceramic body along the flow axis. The microwave applicator receives microwaves from the microwave source through a single waveguide feed. The inventive apparatus which is provided adjacent the die end of an extruder, supplies substantially greater continuous and substantially uniform circumferential volumetric heating to the wet ceramic body than standard methods.

[0007] The invention is applicable to any plastically deformable material which is capable of being molded and shaped by extrusion. Such materials include mixtures of inorganic powders (i.e., ceramic raw materials) and organic forming compounds (i.e., binders, surfactants, plasticizers, lubricants, and the like). At least one organic compound has a thermal gel point, this typically being a binder component. Particularly suitable plastic materials are mixtures capable of forming ceramic articles which contain cordierite and/or mullite. Examples of such mixtures being 2% to 60% mullite, and 30% to 97% cordierite, with allowance for other phases, typically up to 10% by weight. Some ceramic batch material compositions for forming cordierite are disclosed in U.S. Pat. No. 3,885,977. Suitable binders for cordierite formation which have a thermal gel point are cellulose ether binders, such as methylcellulose, and/or methylcellulose derivatives.

[0008] The ceramic raw materials, binder and remaining organic components are mixed with a liquid vehicle, generally water, to form a plasticized batch. The

batch is then extruded through a die. Extruders are well known in the art, and can comprise a ram or a screw feed that forces the material through the die. As the ceramic material leaves the extruder die it is in the shape of a long tubular mass, referred to as a "log" which is then cut to shape. The invention is particularly suited to the process of extruding ceramic substrates. In past practice, the as-extruded log has a generally low wet strength, and is not generally firmly self supporting due to very thin webs. This makes the log difficult to handle in later processing steps (i.e., wet handling, cutting, and drying) without causing damage, such as through deformation.

[0009] According to the invention, after leaving the extrusion die, the ceramic log enters a field of microwave energy. The log is exposed to microwaves, while being conveyed at a rate sufficient to heat above the gel point of the binder. This causes the wet ceramic body to stiffen, thereby preventing sagging or handling deformation which is likely to occur when the shaped body has a low wet strength and is therefore not wholly self-supporting. Gelling in the organic binder occurs due to cross-linking of the polymer chains as known in the art. However, there is substantially no evaporation or water loss which occurs in ceramic bodies stiffened according to the present invention. This is an important advantage of this invention as it therefore prevents defects associated with shrinkage. The invention also allows for a more efficient and less costly ceramic substrate forming process.

Brief Description Of The Drawings

[0010] The invention may be further understood with reference to the following drawings, wherein:

[0011] FIG. 1 is a schematic representation showing generally the microwave stiffening system according to the present invention;

[0012] FIG. 2 is a perspective view of an embodiment of a microwave applicator with a chamber composed of a modified rectangular waveguide;

[0013] FIG. 3 is a cross-sectional view illustrated along line 3-3 of the embodiment of FIG. 2;

[0014] FIG. 4 is a cross-sectional view illustrated along line 5-5 of the embodiment of FIG. 2;

[0015] FIG. 5 is a top view of the outlet end of the microwave applicator of FIG. 2 showing attenuation means;

[0016] FIG. 6 is a bar graph showing the effect of microwave heating on a cordierite honeycomb structure having a cell density of 600 cells per square inch and 0.004 inch thick cell walls;

[0017] FIG. 7 is a perspective view of another embodiment of a microwave applicator with a chamber composed of first and second cylindrical sections arranged in a diametrically stepped geometry;

[0018] FIG. 8 is a cross-sectional view illustrated along the line 8-8 of the embodiment of FIG. 7; and,

[0019] FIG. 9 is a cross-sectional view illustrated along the line 9-9 of the embodiment of FIG. 7.

Detailed Description Of The Invention

[0020] FIG. 1 illustrates the main features of the invention in a schematic fashion for a microwave stiffening system 10. A ceramic log 12 leaves a forming member or extruder 14 and is conveyed through a microwave applicator 16. Accordingly, the microwave applicator 16 is located at the exit or die end of the extruder 14 such that immediately upon being formed by the die member the ceramic log 12 is exposed to a field of microwave energy.

[0021] The microwave applicator 16 includes a chamber 20 and a single waveguide feed 28. Chamber 20 is outfitted with an inlet end 22 and an outlet end 24 in combination with a support 18 for carrying the log 12. Support 18 relates to any means as known in the art for continuously moving bodies, and preferably includes an air bearing system comprising a series of air bearing support chambers that are each supplied with air through individual conduits each of which is connected to a common air supply pipe, as described in U.S. Pat. No. 5,205,991 which is herein incorporated by reference in its entirety.

[0022] A single waveguide feed **28** is provided in communication with the microwave source **32** for receiving microwaves into the microwave applicator **16**. A single waveguide feed is advantageous in the inventive apparatus for design simplification and cost reduction.

[0023] Attenuation means **26** are generally provided when necessary to reduce microwave radiation leakage at the inlet **22** and outlet **24** ends. Means for reducing microwave radiation are well known in the art, and can include microwave attenuators and chokes. Impedance matching means **30** are generally also provided between the microwave source **32** and the waveguide feed **28** to stop the reflection of microwave energy in a reverse direction. Such suitable devices include circulators and stub tuners as known in the art.

[0024] The microwave source **32** transmits microwaves in frequency range of 100 MHz to 30 GHz. The microwave source **32** can include any appropriate source such as a magnetron, klystron, traveling wave tubes, oscillator and the like. The system is also generally provided with a power supply and controller **34** for controlling and adjusting the microwave radiation delivered to the microwave applicator **16**. The microwave energy is provided in a succession of TE_{xy} and/or TM_{xy} waveguide modes, where x is between 0 and 8, and y is between 1 and 3.

[0025] FIG. 2 illustrates an embodiment of a microwave applicator **40** suitable for the microwave stiffening system of the invention. FIGS. 3 and 4 illustrate cross-sectional views taken along lines 3-3 and 5-5 respectively. Microwave applicator **40** comprises a chamber **42** composed of a rectangular waveguide **52** bent along its length at two 90° angles such as in the shape of a "U"-structure. It is also contemplated that a square waveguide with a square waveguide feed would also be suitable in the present invention.

[0026] In operation most of the microwave energy is supplied to the ceramic log **12** in two 90° turns. In the first turn microwave energy enters the chamber through the microwave feed **48**, passes through the ceramic log **12** doubles back on it self, where it is then reflected by the short at **54**. The short **54** serves to reflect the power back into the 90° turns, thereby taking a second pass through the ceramic log **12**. The microwave energy is provided in the TE_{11} waveguide mode at the ceramic log inlet and outlet.

[0027] Cylindrical inlet **44** and outlet **46** ends allow for passage of ceramic log **12** through chamber **42**. Ceramic log **12** is shown to be conveyed via an air bearing support **50** as discussed above. Inlet **44** and outlet **46** ends are preferably outfitted with attenuation means **56** as shown in FIG. 5 (only shown for outlet end **46**). Attenuation means **56** include three parallel rows of screws extending in the cavity **46a** of the outlet end **46** to surround the ceramic log **12** exiting there through. This simple arrangement has been found to be an effective method of reducing microwave radiation in the present invention. A microwave input port is provided at **48**.

[0028] A laboratory-scale microwave stiffening apparatus having the following dimensions was built and tested on extruded cordierite-forming material. In FIG. 4, $A=0.257$ m, $B=0.257$ m, $C=0.096$ m, $D=0.610$ m, $E=0.102$ m, and $F=0.154$ m. The microwave source is a magnetron having a frequency of 2.45GHz and a 1.8 kW power source, such as models available from ASTeX®. The cordierite-forming material was extruded through a honeycomb-forming die to form a tubular log with a traverse cross section of substantially round dimensions with major and minor axes of about 1.5 inches, and a cellular density of 600 cells per square inch and 0.004 inch thick cell walls. For experimental purposes as the ceramic log exited the extruder die it is passed through the microwave applicator at a feed rate of 40 lbs/hour. The power source is varied to between approximately zero watts (no microwave stiffening) to 600 watts. The stiffness of the ceramic log is measured using the ball drop test. This test involves dropping a rounded weight onto a supported wet honeycomb structure. The depth to which the weight sinks into the body is measured. High readings indicate a soft body, and low readings a stiffer body.

[0029] Referring now to FIG. 6 therein shown are the results for the ball drop testing, as indicated in mm, as a function of power level, as indicated in watts. As the power to the microwave applicator is increased, the ball drop measurements decrease indicative of a stiffer material. Ball drop decreases by 35% at about 600 watts indicating significant increase in the stiffness of the ceramic extruded log.

[0030] Using both Finite Difference Time Domain (FDTD) method which is based on an electromagnetic modeling algorithm, and a visualization software, such

as Tecplot, a microwave stiffening system can be fully designed based on dielectric properties of the ceramic extruded material, the dimensions of the microwave applicator (from FIG. 4), and an application of a frequency of 915 MHz. Accordingly, another embodiment in accordance with present invention is illustrated in FIGS. 7-9.

[0031] A microwave applicator **60** comprises a chamber **62** which transforms microwave energy from the microwave source into a cylindrical waveguide mode. As shown, chamber **62** is composed of an inner **64** cylindrical section and an outer **66** cylindrical section of larger diameter. The outer cylindrical section **66** surrounds inner cylindrical section **64** to create a diametrically stepped geometry. Inner cylindrical section **64** receives and exits ceramic log **12** at inlet **68** and outlet **70** ends, respectively.

[0032] Outer cylindrical section **66** includes waveguide feed **72** for receiving microwaves into chamber **62**. Portions of the inner cylindrical section **64** are cut along the circumference thereof to form a pair of adjacent curvi-planar segments **74**, as shown in FIG. 8. A first cut-out portion **76** is adjacent and corresponds to waveguide feed **72**. A second cut-out portion **78** extends between curvi-planar segments **74**. The curvi-planar segments **74** are long enough to shield a half-wavelength section of the ceramic log **12**, measured from the center of the first cut-out portion **76**.

[0033] The function of the curvi-planar segments **74** is to evenly distribute microwave energy entering cylindrical waveguide **62** such as to provide uniform circumferential heating of ceramic log **12**. Specifically, as microwaves are transmitted through microwave input port **72**, a portion thereof enters through first cut-out **76**, while the remaining is deflected by planar segments **74** to enter second cut-out **78**, for uniform circumferential heating. The modeling simulations shows that the microwave energy is provided in a succession of TE_{x1} waveguide modes, where x is between 3 and 4, so as to more evenly distribute the concentrations of microwave energy to the ceramic log. To excite these higher order modes the diameter of the outer cylindrical section **66** is scaled to the thickness of waveguide.

[0034] A person of ordinary skill in the art will appreciate further features and advantages of the invention based on the above-described embodiments.

Accordingly, the invention is not limited by what has been particularly shown and described, except as indicated in the appended claims.